INL/CON-12-25487
PREPRINT

Status of the NGNP Fuel Experiment AGR-2 Irradiated in the Advanced Test Reactor

HTR 2012

S. Blaine Grover
David A. Petti

October 2012

Proceedings of the HTR 2012
Tokyo, Japan, October 28 – November 1, 2012
Paper HTR2012-3-029

Status of the NGNP Fuel Experiment AGR-2 Irradiated in the Advanced Test Reactor

S. Blaine Grover and David A. Petti
Idaho National Laboratory
P.O. Box 1625, Idaho Falls, Idaho, 83415, United States of America
phone: 208-526-4489, Blaine.Grover@inl.gov

Abstract – *The United States Department of Energy's Next Generation Nuclear Plant (NGNP) Advanced Gas Reactor (AGR) Fuel Development and Qualification Program will be irradiating up to seven separate low enriched uranium (LEU) tri-isotopic (TRISO) particle fuel (in compact form) experiments in the Advanced Test Reactor (ATR) located at the Idaho National Laboratory (INL). These irradiations and fuel development are being accomplished to support development of the next generation reactors in the United States, and will be irradiated over the next several years to demonstrate and qualify new TRISO coated particle fuel for use in high temperature gas reactors. The goals of the irradiation experiments are to provide irradiation performance data to support fuel process development, to qualify fuel for normal operating conditions, to support development and validation of fuel performance and fission product transport models and codes, and to provide irradiated fuel and materials for post irradiation examination (PIE) and safety testing. The experiments, which will each consist of at least six separate capsules, will be irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control of each capsule. The sweep gas will also have on-line fission product monitoring on its effluent to track performance of the fuel in each individual capsule during irradiation.*

The first experiment (designated AGR-1) started irradiation in December 2006 and was completed in November 2009. The second experiment (AGR-2), which utilized the same experiment design as well as control and monitoring systems as AGR-1, started irradiation in June 2010 and is currently scheduled to be completed in April 2013. The design of this experiment and support systems will be briefly discussed, followed by the progress and status of the experiment to date.

I. INTRODUCTION

The AGR fuel development and irradiations are being performed to support development of the next generation reactors in the United States. The AGR Fuel Development and Qualification Program, which is part of the NGNP Program, will complete the irradiation of the experiments over the next five to six years to demonstrate and qualify new LEU TRISO particle fuel for use in high temperature gas-cooled reactors. The goals of the irradiation experiments are to provide irradiation performance data to support fuel process development, to qualify fuel for normal operating conditions, to support development and validation of fuel performance and fission product transport models and codes, and to provide irradiated fuel and materials for post irradiation examination (PIE) and safety testing [1].

The experiments, which will each consist of multiple separate capsules, will be irradiated in an inert sweep gas atmosphere with individual on-line temperature monitoring and control of each capsule. The sweep gas will also have on-line fission product monitoring on its effluent to track performance of the fuel in each individual capsule during irradiation.

The experiments are designed for the specific irradiation position and its size, as well as the irradiation parameters (e.g. temperature, fluence, etc.) necessary to achieve the experiment objectives. The experiments employ an umbilical tube to house and protect the instrumentation and gas lines from the experiment capsules up to their connections at the reactor vessel wall to the monitoring, control and data collection systems. The overall capsule design concept and sweep gas systems used to control the capsule temperatures and to monitor for fission gas release will be common to all of the AGR fuel experiments. In addition, the experiment capsule design was identical for the first (AGR-1) and the second (AGR-2) experiments, but will be extensively modified for the third and later irradiations. The design modifications will be necessary to support the specific objectives of the future irradiations as well as to accommodate the different type of irradiation position to be used. The mission, capsule design and support systems for the AGR-2 experiment will be discussed followed by the status and the irradiation results to date.

II. EXPERIMENT TYPE, MISSION AND IRRADIATION POSITION

The following subsections detail the experiment type, mission and irradiation position within the ATR core selected for the AGR-2 experiment.

II.A. Experiment Type

AGR-2 is an instrumented lead type experiment with on-line active temperature control and fission product monitoring of the effluent gas. The other major type of irradiation experiment commonly performed in the ATR is a static capsule experiment, which has only passive temperature control and the experimental results are determined after the irradiation by examination in a hot cell. The experiment capsules utilize an insulating gas jacket with variable mixing of helium and neon sweep gases to control temperature of the fuel during irradiation. The overall concept for temperature control of the experiment capsules, as well as the specific temperature control and fission product monitoring systems used on AGR-2 are the same identical systems initially installed and used for AGR-1.

II.B. Mission

The primary mission for AGR-2 is to test production scale fuel versus the laboratory scale fuel irradiated in the first experiment (AGR-1). In this capacity, AGR-2 will provide valuable feedback, both during irradiation and from post irradiation examination, to support further development and fabrication of the fuel to be used in the actual fuel qualification irradiations planned as AGR-5 and AGR-6.

The fuel irradiated in AGR-1 was exclusively uranium oxycarbide (UCO) type fuel fabricated on a laboratory scale and included several different variants in the TRISO coating used on the fuel particles. However, a secondary function of AGR-2 is to irradiate both UCO and uranium dioxide (UO_2) type fuels, both of which were fabricated on a production scale.

Finally, as part of the Generation IV (GEN IV) International Forum, two capsules in AGR-2 were offered to other GEN IV countries. France and South Africa accepted this offer to irradiate fuel in support of their gas reactor development programs. Therefore, fuel in one AGR-2 capsule contains fuel fabricated in France as part of their Very High Temperature Reactor (VHTR) program, and a second capsule contains fuel from the Pebble Bed Modular Reactor (PBMR) program in South Africa. However, the fuel and irradiation details provided in this paper only encompass the NGNP program fuels since the fuel and irradiation details for the French and South African fuel are beyond the scope of this paper and are protected under their confidentiality agreement with the INL. Since there are many additional details of the fuel (e.g. fuel kernel and particle size, fuel compact dimensions, enrichment levels, etc.) as well as irradiation requirements (e.g. burnup levels, temperatures, etc.) the fuel will be discussed further in a separate section.

II.C. Irradiation Position

AGR-2 is being irradiated in the west large B position (B-12), similar to the east large B position used to irradiate AGR-1 (B-10). These different irradiation positions are shown in Figure 1. The large B positions (38 mm diameter) were chosen for the AGR fuel irradiations since the rate of fuel burnup and fast neutron fluence accumulation in these positions would provide an acceleration factor of between one and three times that expected in the

Very High Temperature Reactor (VHTR). This acceleration factor was high enough to accomplish the irradiation within a reasonable time, but yet low enough to avoid possible premature fuel particle failures similar to those experienced in past highly accelerated particle fuel tests.

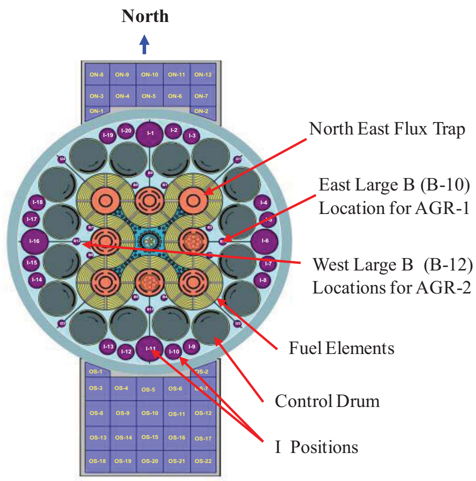

Fig. 1: ATR core cross-section showing AGR-1 and AGR-2 irradiation locations.

AGR-2 is being irradiated in B-12 instead of B-10 to maximize the use of the planned power levels in the ATR and to achieve the irradiation goals of AGR-2. These positions have a nominal fast neutron flux of 2.5 x 10^{14} n/cm^2-s and a thermal neutron flux of 1.61 x 10^{13} n/cm^2-s. The AGR experiments were originally planned to be irradiated in pairs using the B-10 and B-12 irradiation positions concurrently to minimize the schedule necessary to complete the irradiations. However, it later became apparent that in order to achieve the fuel irradiations in the time required to support the NGNP Program schedule, the irradiations would have to be accelerated. Therefore, the successive AGR experiments (AGR-3 through AGR-8) have tentatively been scheduled for irradiation in the much larger ATR north east flux trap (NEFT) position shown in Figure 1.

III. FUEL AND IRRADIAITON DETAILS

As indicated earlier, in contrast with AGR-1, the AGR-2 experiment contains both UCO and UO_2 TRISO type fuels, which are different in many ways besides the fuel type (e.g. enrichment, fuel kernel and particle size, particles/compact, etc.) [2]. In addition, the UCO type fuel in AGR-2 is also different in enrichment, kernel size, etc. from the UCO fuel irradiated in the AGR-1 experiment.

Each NGNP experiment capsule in AGR-2 contains 12 prototypical right circular cylinder fuel compacts nominally 12.4 mm in diameter and 25 mm long. The fuel is comprised of LEU fuel kernels, which are covered with a layer of silicon carbide, sandwiched between two pyrolytic carbon layers to make up the TRISO-coated fuel particles. The fuel particles are over-coated with a thermo-set resin and pressed into fuel compacts that are then sintered to remove the volatile compounds in the resin. The following subsections describe each type of fuel as well as their irradiation requirements.

III.A. UCO Fuel and Irradiation Details

The AGR-2 UCO fuel type was fabricated from 14.0% enriched LEU into 425 μm nominal diameter fuel kernels, which after being covered with the TRISO coatings result in 870 μm nominal diameter fuel particles. Approximately 3,150 fuel particles are contained within each fuel compact resulting in an approximate mean total uranium content of 1.3 grams.

Three capsules in AGR-2 contain this type of fuel, with one of them being irradiated at a higher temperature. The purpose of the high temperature capsule is to obtain early data on the UCO fuel performance at slightly elevated operating temperatures. One of the other capsules with this fuel type is located at the very top edge of the test train. This capsule will be exposed to a lower neutron flux, which will result in lower fuel burnup compared to the burnup levels in the two other capsules containing this fuel type. Since this capsule was located in a low neutron flux and the other two capsules (including the high temperature capsule) were in located in intermediate flux positions, the burnup goal for this fuel type was set at 10% FIMA for the majority of the fuel compacts with a minimum compact average burnup of 7% FIMA. The anticipated burnup ranges from approximately 7.3% FIMA for the very top capsule exposed to the lowest neutron flux rate to almost 13.9% FIMA for the capsule at the intermediate position just below the vertical center of the ATR core. The capsule time average peak temperature requirement for the high temperature capsule was set at < 1400 ºC, and the capsule time average peak temperature requirement in the other two UCO capsules will remain at the same of <1250 ºC value used for the UCO fuel in

AGR-1. The capsule time-average volume-average temperature goals have been set at >1150 ºC for the high temperature capsule, and >1000 ºC for the other two UCO capsules.

III.B. UO_2 Fuel and Irradiation Details

The UO_2 fuel type for AGR-2 was fabricated from 9.6% enriched LEU into 510 µm nominal diameter fuel kernels, which result in 950 µm nominal diameter fuel particles after the TRISO coatings are applied. Approximately 1,520 fuel particles are contained in each fuel compact with an approximate mean total uranium content of 1.0 gram. Since three positions contained UCO capsules, there was only room for one UO_2 fuel capsule for the AGR program, and it is located at the vertical center of the ATR core. The burnup requirements for this fuel are 10% FIMA for the compact average burnup goal for a majority of the fuel compacts and a minimum of 7% FIMA in each fuel compact. To simulate irradiation conditions in a pebble bed reactor, the irradiation temperatures are lower than those used for the UCO fuel because fuel temperatures in a pebble bed are lower than in prismatic gas reactors. The capsule time-average peak temperature requirement was set at < 1150 ºC, and the capsule time-average volume-average temperature goal is > 900 ºC.

IV. CAPSULE AND CONTROL AND MONITORING SYSTEM DESIGNS

The experiment test train for the AGR-2 irradiation consists of six separate stacked capsules vertically centered in the ATR core. Each capsule has its own custom blended gas supply and exhaust for independent temperature control, and the effluent temperature control gas from each capsule is independently (and continuously) monitored for specific fission gases. The following subsections provide details of the irradiation capsule and test train design as well as the monitoring and control systems design and function.

IV.A. Capsule Design

A horizontal cross-section of the AGR-2 experiment capsule is shown in Figure 2 and a vertical section is shown in Figure 3. The experiment capsules are approximately 35 mm in diameter and 150 mm in height - including the plenums between adjacent capsules. Each capsule contains 12 prototypical right circular cylindrical fuel compacts nominally 12.4 mm in diameter and 25 mm long. The compacts are arranged in four layers in each capsule with three compacts per layer nested in a triad configuration as shown in Figure 2.

A nuclear grade graphite holder surrounds and separates the three fuel compact stacks in each capsule to prevent any fuel particles on adjacent compacts from touching each other, which could possibly cause a premature particle failure. Very thin (0.5 mm or less) graphite top and bottom end caps on the compacts prevent particle to particle contact between adjacent axial compacts.

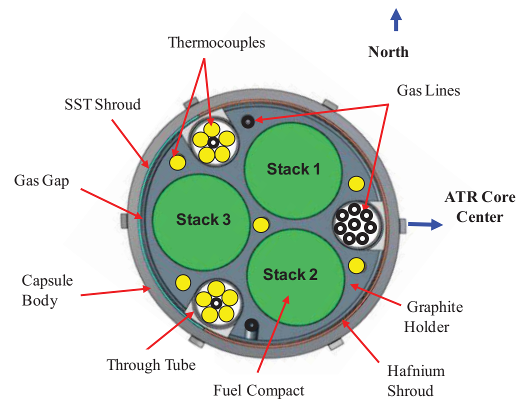

Fig. 2: AGR-2 experiment capsule cross-section

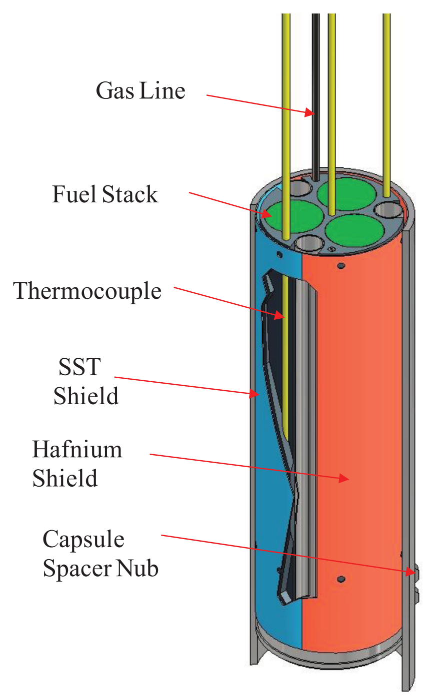

Fig. 3: AGR-2 experiment capsule vertical section

The graphite holder also provides the inner boundary of the insulating gas jacket (approximately 0.25 mm to 1.0 mm thick depending on vertical location within the reactor core) for temperature control of the fuel during irradiation. Boron carbide is dispersed in the graphite holder to serve as a consumable neutron poison. In addition to the boron carbide, a thin (0.25 mm thick) hafnium shield next to the outside capsule wall surrounds the two fuel compact stacks facing toward the center of the ATR core (stacks 1 and 2 shown in Figure 2). A thin (0.25 mm thick) stainless steel shield next to the outside capsule wall blankets the other fuel compact stack (stack 2 shown in Figure 1) located on the side of the capsule facing away from the ATR core. A stainless steel shield versus hafnium was used on this side of the capsule to minimize the effects on the neutron flux to these already lower powered fuel compacts while retaining the same insulating gas jacket to maintain the proper irradiation temperature.

The neutron poisons were necessary to limit the initial fission rate in the fuel and thereby provide a more consistent fission rate during irradiation. As the boron carbide is consumed in the graphite, the fission rate in the fuel reaches a peak at about the mid-point of the irradiation and then slowly decreases as the fuel continues to burnup. Reducing and controlling the initial fission rate in this manner decreases the ratio of the maximum to minimum heat generation rates in the fuel, which provides better temperature control in the fuel during the rather long irradiations that are in excess of two years.

Besides protecting the fuel and providing an inner boundary for the insulating gas jacket, the graphite holder also has features machined to accommodate the thermocouples for measuring temperature within the capsule and the three through tubes containing the gas lines and thermocouples for adjacent capsules. The through tubes are positioned very precisely in the top and bottom heads of the capsules so they can also be utilized to center the graphite in the capsule and provide the necessary gas jacket for temperature control. Based upon the experience gained in AGR-1, only the larger size thermocouples used in AGR-1 were used in AGR-2, which resulted in two thermocouples per capsule with the exception of the top capsule which has five thermocouples (as did AGR-1). No metal (only graphite and inert gas) was allowed to come in contact the fuel particles to (again) prevent premature fuel particle failures, so the thermocouples measure the graphite temperature and the corresponding fuel temperatures are calculated based upon the measured temperatures in the graphite. Melt wires were included in each capsule for passive temperature verification in the event that all thermocouples within a capsule were to fail during irradiation. This situation was anticipated to happen in at least some of the capsules due to the long irradiation time and the very high temperatures at the thermocouple locations. Flux wires were also installed in the graphite to measure both the thermal and fast neutron fluence. Since the outside diameter of the graphite establishes the inner boundary of the insulating gas jacket, it varies among the capsules depending on the neutron flux rate at the vertical location of the specific capsule within the ATR core. The boron carbide content in the graphite spacer is also different in the capsules as a result of the chopped cosine shaped vertical neutron flux profile in the ATR.

IV.B. Test Train Design

The four NGNP capsules and the two Gen IV partner capsules were welded together to form the core section of the AGR-2 test train. The core section is welded to an umbilical tube (termed a lead-out) that houses and protects the gas lines and thermocouple leads from the experiment capsules to the reactor vessel wall penetration. Outside the reactor vessel wall, the gas lines and thermocouple leads are connected to their facility counterparts in the temperature monitoring, control and data collection system. The lead-out also vertically locates the experiment within the large B irradiation position in the ATR core.

In essence, limiting the acceleration factor on the fuel burn-up also determined the irradiation time for the AGR experiments since the neutron flux is one of the major controlling factors for the irradiation time. The AGR irradiations each have their own FIMA burnup requirements, which in conjunction with the fuel enrichments and the neutron flux in the Large B positions resulted in the rather long (in excess of two years) irradiation times for the AGR-1 and AGR-2 irradiations. Along with the long irradiation times, these requirements also resulted in a significantly reduced heat generation rate towards the end of the irradiation. As indicated earlier, every effort was made to flatten the heat generation rate curve as much as possible to increase the controllability of the temperatures at the end of the irradiation. This controllability was necessary to meet the time-average volume-average temperature requirements during irradiation while staying below the time-average and the instantaneous peak temperatures. The combination of these requirements provided some significant challenges in the design of the AGR experiments and their control systems.

The two different fuel types with widely different enrichments, different fuel particle numbers per compact, burnup requirements, etc. presented additional challenges in the design of the AGR-2 capsules and incorporating them into a single test train. However, some of these differences were used to help offset the effects of other differences, and the result was an efficient design and use of the ATR core space. One key parameter used in this optimization was the placement of the different fuel types and enrichment levels in the vertical neutron flux profile of the ATR core. This variable was utilized by placing the low enriched UO_2 fuel at the center of the core where the neutron flux is highest and placing the higher enriched UCO fuel towards the edges of the test train in the slightly lower neutron flux areas. This vertical placement scheme helped to balance the effects of the different enrichments (with their associated different burnup requirements) and therefore achieve the required uniform irradiation time for the experiment. Since the experiment utilizes active monitoring and control, it is not possible to remove individual capsules at different irradiation times without reconstitution of the test train in a hot cell facility, which was determined to be cost prohibitive for this program. The other variable used to help offset the effects of fuel loading and burnup requirements was the boron concentration in the graphite holders. The boron concentration is approximately 25% less for the lower enriched UO_2 fuel in the center of the test train than the concentration used for the higher enriched UCO capsules located within the test train in areas of slightly lower neutron flux. In the same way, the boron concentration in the outermost UCO capsule located in the lowest neutron flux region of the test train is approximately 15 % less than the UCO fuel capsule located in the higher flux region.

IV.C. Temperature Control System

The AGR-2 irradiation is utilizing the seven channel temperature system originally developed for the AGR-1 irradiation. The desired temperatures in the experiment capsules are achieved by adjusting the mixture ratio of two gases with differing thermal conductivities to control the heat transfer across an insulating gas jacket between the heat source (fuel fissions and gamma heating of capsule materials) and the relatively cold reactor coolant (52 ºC). The AGR-2 experiment gas flow path is shown in Figure 4.

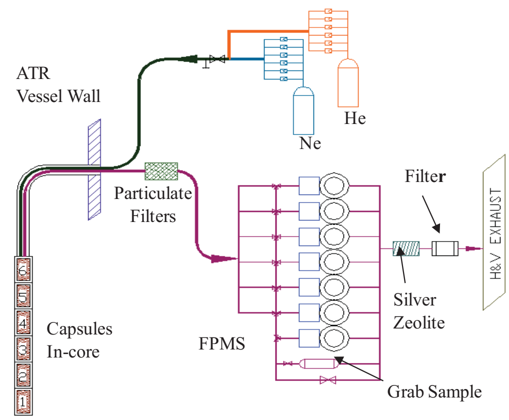

Fig. 4: AGR-2 experiment flow path

Helium is used as the high (thermally) conductive gas and since the AGR experiments are fuel irradiations, neon is used as the insulating gas. Neon (versus argon that can provide a wider temperature control band) is typically used in fuel irradiations for the insulating gas to avoid the effects of activated argon gas, which can overwhelm the fission product monitors. Computer controlled mass flow controllers are used to automatically blend the gases (based upon feedback from the experiment thermocouples) to control the temperatures at the thermocouple locations, which are then analytically coupled to the fuel specimen temperatures. The thermocouples are located in the graphite holder (shown in Figure 2) inside each experiment capsule with one thermocouple being designated for primary control of the capsule temperature. In the event the control thermocouple fails open (as indicated by a significant increase in resistivity), temperature control for the capsules will automatically be switched over to the other (back-up) thermocouple, which will then be designated as the new control thermocouple. A more comprehensive description of the AGR temperature control system design and functions can be found in Reference [3].

IV.D. Fission Product Monitoring System

In order to minimize temperature changes and maintain the temperature as constant as possible, the temperature control system provides a continuous purge gas flow to each specimen capsule. Monitoring this continuous gas flow for fission gases can provide valuable information on the fuel performance during irradiation. As shown in figure 4, the outlet gas from each capsule is routed to individual fission product monitors, and the gas flows can be redirected to an online spare monitor if any monitors experience detector or other failures. There is also the capability to take a grab sample of the effluent gas from each capsule.

The fission product monitors consist of a high purity germanium spectrometer for identifying and quantifying the fission gas nuclides and a sodium iodide liquid scintillation gross gamma detector to provide indication when a puff release of fission gases passes through the monitor. The gross gamma detector also provides the release timing. With the combination of a gross gamma detector and a spectrometer being continuously on-line, the gross gamma detector results can be scanned quickly to determine which portions of the voluminous spectrometer data need to be closely scrutinized. A puff release of fission gases typically indicates when a TRISO fuel coating failure may have occurred.

Through identification and quantification (with uncertainties) of the isotopes, the spectrometer can be used to determine the isotopic release-to-birth ratio (with uncertainties) of the fission gases being detected. The determination of the release-to-birth ratios can establish whether a new TRISO fuel coating failure has occurred or if the fission products are merely being released from an existing failure or uranium contamination on the outside surface of the fuel particles. These details can be very important in the qualification of fuel especially in small TRISO particle fuels, where only a very few random particle failures are anticipated and need to be tallied very accurately to support statistical qualification of the fuel.

The fission product monitoring system was designed and the response modeled to detect and quantify each individual fuel particle failure up to and including a very unlikely 250th fuel particle failure. A more comprehensive description of the AGR fission product monitoring system design and functions can be found in Reference [3].

V. EXPERIMENT STATUS AND RESULTS

The following subsections provide details on the design, status and results of AGR-2 experiment irradiation.

V.A. AGR-1 Design and Assembly Feedback

A variety of tests were conducted prior to the AGR-1 test train fabrication and assembly, including the high temperature thermocouple testing and testing of the gas leakage through the very tight slip fit between the through tubes and the capsule bottom heads [3]. Development and testing was also conducted on various capsule assembly processes (i.e., clearances, welding, thermocouple brazing, etc.) to ensure the assembly of the test train could be accomplished as designed. The lessons learned from these tests and special process development were applied to the design and assembly of the AGR-2 experiment.

There were also lessons learned in the capsule materials used in AGR-1 that were applied to the design of AGR-2. The capsule through tubes used in AGR-1 were molybdenum, but the through tube material was changed to niobium for AGR-2. This change was done to reduce the types of different materials being seal brazed simultaneously to the capsule top head. In a similar manner, there were molybdenum sheaths on the large (2.4 mm diameter) type N thermocouples, Inconel sheaths on the standard (1.5 mm diameter) type N thermocouples, niobium sheaths on the INL developmental Mo-Nb thermocouples and niobium gas lines used in AGR-1. However, in AGR-2 niobium was used for all of the thermocouple sheaths, gas lines and through tubes, which greatly simplified the top head brazing process.

A new technique was also developed during the assembly of AGR-2 to swage the bottom of the through tubes tightly into the slip fit holes in the capsule bottom heads. This new technique greatly reduced the flow of the leadout gas into each capsule while also significantly improving the consistency of the leadout flow rate into the six different capsules. Reducing the leadout flow into each capsule minimizes the dilution of the temperature control gas mixture being supplied to the individual capsules, which then increases the temperature control of the capsules.

Unfortunately, a through tube in one of the NGNP capsules developed a leak inside the capsule during final assembly. The through tube leak could potentially (greatly) increase the portion of the leadout gas flow entering that specific capsule, which would reduce the gain in temperature control from swaging the through tubes in the capsule bottom head. However, a design change to the gas control system was developed, which added flow control valves to manipulate the effluent gas back pressure within each capsule. Controlling the effluent gas back pressure in each capsule provided the ability to balance the leadout flow going into all six capsules, which (again) prevented dilution of the temperature control gas mixture and therefore allowed better temperature control of the individual capsules. It should also be noted that the effluent gas back pressure was controlled without affecting the critical effluent gas delivery time between the capsules and the fission product monitors. The effluent gas delivery time is a very important parameter used to balance the decay of activated neon temperature control gas while also minimizing the loss of short lived fission gases. The design to modify the temperature control system and install the flow control valves has been completed and the modifications were installed in early calendar 2011.

V.B. AGR-2 Schedule and Irradiation Experience

Assembly of the AGR-2 experiment test train was completed in May 2010, and it was inserted into the ATR west large B position (B-12) in June 2010 to start its irradiation. Leadout flow testing and measurement of the effluent gas delivery time between each capsule and its corresponding fission product monitor were completed in July 2010, and the experiment was then taken to temperature.

The performance of the larger type N thermocouples has been mixed. The infant mortality rate of the thermocouples during test train assembly and insertion into the reactor was typical (one failed thermocouple out of the fifteen installed) for a test train of this complexity, especially considering the brazing, bending and handling operations involved. Unfortunately, this thermocouple was located in the high temperature capsule. In addition, the other thermocouple in the high temperature capsule failed during the third ATR operating cycle of the irradiation. Failure of the thermocouples in this capsule was anticipated due to the much higher operating temperature than the other capsules. The risk associated with early thermocouple failures was deeply considered and accepted during evaluation of whether to add this requirement to the experiment, especially since the thermocouples had already been selected and procured for the test train.

Unfortunately, both thermocouples in another UCO capsule failed at the end of the fourth irradiation cycle, and three of the five thermocouples have also failed in the very top (or sixth) capsule that also contains UCO type fuel. These failures were much earlier than anticipated, even in the high temperature capsule. However, they have been mitigated by using the thermal analysis model to calculate the necessary gas mixtures for the capsules to maintain their desired operating temperatures. The analysis model was reconciled against measured operating temperatures in the capsules during the first three operating cycles to increase its accuracy in gas mixture calculations. This same technique was employed towards the end of the AGR-1 irradiation when the anticipated thermocouple failures occurred that were the result of very high thermocouple operating temperatures over very long durations [4]. A new process utilizing the NGNP statistical data evaluation program is also being used to help predict the gas mixture based upon the gas mixture changes occurring in the other AGR-2 capsules on a weekly basis. The statistical gas mixture predictions are verified (as deemed necessary) using the thermal analysis model. This new process is proving to be easier with faster response times to the changes in the reactor operating conditions during the experiment irradiation.

There was a short high power operating cycle for the ATR in the early fall of 2011, which would have resulted in excessive temperatures in the AGR-2 fuel, so the experiment was removed from the ATR during this cycle. Since the experiment is being operated at temperatures up to 1400°C, the experiment capsule internal components can become very brittle and delicate. Unfortunately, the handling required to remove and reinsert AGR-2 into the ATR core appears to have resulted in some possible shifting or damage to these delicate components (e.g. gas lines). This damage has been evidenced by gas flow anomalies in the experiment, which have resulted in essentially uncontrollable leakage between most of the experiment capsules. Leakage between capsules can impact both temperature control of the individual capsules as well as the fission product data from each of the capsules.

Fortunately, the boron carbide had been depleted and the peak fuel burnup was well over halfway to the irradiation goal (~9.3% versus 13.9% FIMA) when this regrettable situation occurred. These factors, coupled with all of the capsules having been originally designed to achieve their target temperatures with the same gas mixture ratio of helium to neon and the ability to balance the outlet flows from the capsules, resulted in the ability to achieve reasonable temperatures in all capsules by supplying a uniform gas mixture to the entire test train. The individual capsule temperatures are within a reasonable tolerance (e.g. ± 50°C to 75°C) of the original target temperatures. The uniform gas mixture approach allows the fuel centerline temperatures to be accurately calculated even with leakage between the capsules since the exact mixture in all capsules is known to be the same. There is also the possibility of being able to determine which capsule may have experienced a future particle failure by comparing the size and timing of the fission gas releases detected by the different monitors. The premise for detecting particle failures is the gas path from the capsule containing the failed particle to its individual monitor should be shorter and less tortuous than the path to any other fission product monitor. Therefore the monitor connected to the capsule experiencing a particle failure should exhibit the earliest and largest detection peak of noble fission gases.

V.CB. AGR-2 Results to Date

The irradiation had completed 360 Effective Full Power Days (EFPDs) of irradiation out of the approximate 600 to 650 EFPDs scheduled for this experiment in March 2012. The fuel had attained an approximate peak burnup of 9.3% FIMA during that time, but the early irradiation data are still being verified and validated so final results are not yet available. However, the preliminary results indicate the fuel is performing well and no particle failures have been identified.

VI. CONCLUSIONS

The insights and lessons learned from AGR-1 have been incorporated into the design, assembly and early irradiation of AGR-2. The AGR-2 experiment has completed 360 EFPDs of irradiation, and has attained an approximate peak fuel burnup of 9.3% FIMA. The preliminary data indicate the fuel is performing well and no particle failures have been identified. The results of this experiment will provide valuable data for the qualification of gas reactor particle fuel for the NGNP.

VII. ACKNOWLEDGMENTS

This work was supported by the United States Department of Energy (DOE) under DOE Idaho Field Office Contract Number DE-AC07-05ID14517.

VII. REFERENCES

[1] Petti, D. A., et al, “Technical Program Plan for the Advanced Gas Reactor Fuel Development and Qualification Program”, Idaho National Laboratory Report INL/EXT-05-00465, Revision 1 (August 2005)

[2] Phillips, J. A., et al, “Fabrication and Comparison of Fuels for Advanced Gas Reactor Irradiation Tests”, Proceedings of HTR 2010, Prague, Czech Republic, October 18-20, 2010, Paper 236

[3] Grover, S. B., and Petti, D. A., “Initial Irradiation of the First Advanced Gas Reactor Fuel Development and Qualification Experiment in the Advanced Test Reactor”, Proceedings of Global 2007 Advanced Nuclear Fuel Cycles and Systems, Boise, ID, USA, September 9-13, 2007, Paper 177457

[4] Grover, S. B., et al, “Mission and Status of the First Two Next Generation Nuclear Plant Fuel Irradiation Experiments in the Advanced Test Reactor”, Proceedings of the 18th International Conference on Nuclear Engineering, Xi’an, China, May 17-21, 2010, Paper ICONE18-30139, (2010)